

COMPARISON OF COMMON-VIEW AND ONE-WAY GPS TIME TRANSFER OVER A 4000-KM EAST-WEST BASELINE

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Abstract

We have recently established a stable time scale in the Standards Laboratory at the Santa Clara site of Agilent Technologies to provide a reference for developing and testing GPS time-transfer products. The time scale consists of a high performance cesium frequency standard that is steered to follow UTC(USNO, MC) using the output of a commercial GPS-disciplined oscillator. The disciplined oscillator technique is subject to various errors, such as antenna position, broadcast ephemeris, propagation effects, local multipath, and inaccuracy in the GPS/UTC broadcast correction, as well as instrumental factors. The magnitude of these errors is often time-dependent, and not easy to predict. As a consequence of the long time constant used in the steering loop, the intrinsic frequency noise of the cesium standard is also significant. To provide an independent calibration, and to determine the overall accuracy of the time scale, we also carry out common-view time transfer with USNO according to the BIPM schedule. It is well known that many time-transfer errors are considerably reduced by using the common-view technique. The common-view receiver system is portable, and has been calibrated by short baseline, common-clock operation at NIST. In the paper we will discuss the effects of various factors on the accuracy, stability, and traceability of the time scale. Data extending over about 185 days comparing the 'common-view' and 'one-way' time transfer methods will be discussed and compared with data from an independent system operating at Agilent Laboratories. We estimate the stability of the time scale to be about 10 ns rms, and the traceability to UTC(USNO-MC) to be about 10 ns at the 1 sigma level for measurements averaged over several days. Systematic differences between the one-way and common-view results will be discussed.

1 INTRODUCTION

GPS-Disciplined Oscillators (GPSDOs) are now widely used for time-of-day generators and frequency references in telecommunication systems, for synchronizing computers, and for a variety of general-purpose calibration activities. In a GPSDO, the phase of a local oscillator is autonomously synchronized to a filtered estimate of the time scale given by a GPS receiver using a 'one-way' time-transfer technique. Built-in corrections allow the time to be referenced to the MasterClock of the US Naval Observatory, UTC(USNO MC), which closely approximates UTC. The local oscillator can be a quartz crystal, a rubidium oscillator, or even a cesium standard. The use of a high-performance local oscillator allows short-term noise on the GPS time estimate to be filtered out, and provides some degree of holdover if the GPS signal is temporarily interrupted.

The accuracy of one-way time transfer is subject to a number of sources of error. The intrinsic GPS errors are well understood in the context of positioning, but have different effects on precision in time transfer. Some further GPSDO errors are due to the limitations of the local oscillator and feedback loop. A substantial report on the measured performance of a number of commercially available GPSDO systems, together with an analysis of their accuracy limitations, has recently been published [1]. The report shows that, when carefully installed and operated, these instruments can provide excellent value in providing time traceable to UTC to within 100 ns.

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In the following paper, we present the results of two different experiments in which programmable cesium standards were disciplined to follow UTC(USNO MC) using one-way time transfer. These systems were developed mainly to test GPS products, and functioned as very high quality GPSDOs. Feedback loops with time-constants of several days were used to minimize short-term noise. The resulting time scales were monitored using 'Common-View' (CV) time-transfer measurements. Common view is a more accurate, established, technique that is used worldwide in the construction of the UTC time scale. CV time transfer requires information to be exchanged between the two locations at which clocks are to be synchronized, and is thus not usually considered a real-time method.

The results to be presented demonstrate the existence of significant systematic and random differences between one-way and common-view time transfer in our experiments. The results indicate, however, that the stability of the one-way time transfer technique can be very high. This suggests that a GPSDO that has been accurately calibrated can provide a very good remote realization of the UTC(USNO MC) time scale when all possible biases are taken into account.

2 TIME TRANSFER USING GPS

The principles used by a GPS receiver to estimate the time error of its internal clock are widely understood [2]. Time receivers are usually stationary, and operate best in a 'position-hold' mode using a fixed estimate of the antenna coordinates. It can easily be shown that Δd_{ui} , the error in the estimate of the bias of the receiver's clock with respect to GPS time using the i -th satellite, can be given by:

$$\Delta d_{ui} = d_{si} - (I_i + T_i + \mathbf{R}_i \cdot \mathbf{r}_{si} - \mathbf{R}_i \cdot \mathbf{r}_u)/c + G_d + M_i + E_i \quad (1)$$

In Equation (1), d_{si} is the bias of the satellite clock with respect to GPS time; I_i and T_i are errors in correcting the satellite geometric range for the effects of the ionosphere and troposphere; \mathbf{R}_i is the unit vector along the direction from the user to the satellite; \mathbf{r}_u is the vector error in the antenna coordinates of the user; \mathbf{r}_{si} is the vector error in the satellite's broadcast position; G_d is the total uncompensated group delay in the receiver, antenna, and antenna cable; M_i represents multipath delay effects; E_i represents noise and any other uncorrected errors in the estimate; and c is the velocity of light. A time receiver simultaneously tracking N satellites with similar errors obtains an optimum estimate of the instantaneous clock bias by averaging the N estimates given by Equation (1). Multi-satellite tracking is clearly advantageous, since the rms noise due to errors that are not correlated will be reduced by the square root of N . Some of the error sources are, however, correlated, and the importance of a given error depends inversely on the degree of averaging that occurs in a specific application. Each error also has a characteristic correlation time, and thus responds differently to averaging over time. The consequence of each of the errors must therefore be considered in the context of the application. The significance of the group delay G_d is unique to time receivers. The portion of group delay from the receiver itself is generally removed in software, although the delay may be possibly be affected by environmental factors [3,4]. Allowance must be made for antenna and cable group delays, and there may be further effects due to temperature and VSWR [5,6]. When high accuracy is required, these problems can be mitigated by calibrating the receiver, the antenna, and the antenna cable as a unit; this is the practice adopted, for example, by the NIST [7].

3 ONE-WAY TIME TRANSFER USING GPSDOs: NOISE AND ERRORS

Most GPSDOs are currently used by the civilian timekeeping community and employ single-frequency, L1-code receivers. The current GPS constellation contains 27 active satellites of which, in principle, about 12 can be in view at one time from an unobscured location. In a time receiver, it is not useful to track satellites

at very low elevation angles, and an 8-channel receiver is usually adequate. A 12-channel receiver may have some advantages, however, as there will be less competition for channels.

In a GPSDO, the phase of the oscillator, often in the form of a 1 PPS pulse, is compared with the receiver's internal clock after correction for the average bias estimate given by the average of the single-satellite biases given by Equation (1). A servo system then drives the time difference towards zero by controlling the oscillator frequency. The output information from the GPSDO system is contained in the phase of the oscillator and its frequency. The operation of a GPSDO is very similar to that of a phase-locked loop: for times much smaller than the loop time-constant, the noise on the output is that of the oscillator; whereas, at large times, the noise of the GPS time solution dominates. If the loop is at least second-order, there is no average difference between the phase of the output signal and the output of the GPS receiver. This is not true if the oscillator has a significant rate of change of its free-running frequency caused, for example, by frequency jumps.

When a GPSDO is configured to realize UTC time, the receiver uses a correction for the estimated difference between the GPS and UTC(USNO MC) time scales that is part of the GPS navigation message. The accuracy of the correction has been shown to be about 2 ns rms [8], and the correlation time is comparable with the 1-day update rate. Although the difference between UTC and UTC(USNO MC) is usually small, it is important to realize that one-way GPS time transfer realizes an estimate of UTC(USNO MC) rather than the post-calculated UTC time scale.

The short-term noise on the GPS time solution is presently dominated, for all users who are not qualified to decode the P-Y sequences, by the intentional randomization of each of the satellite clock times known as 'Selective Availability' or SA. This is currently a process with an rms amplitude of 75 ns, and a correlation time of about 154 seconds. As of November 1999, all satellites except PRN 15 carry SA, which is uncorrelated from satellite to satellite. At Fourier frequencies below about 1×10^{-3} Hz, SA corresponds to a white-noise spectral density of time with a magnitude of about 3.3×10^{-12} sec² per Hz [9]. In multi-satellite, 'position-hold' operation, the rms noise on the time solution given by Equation (1) is reduced by $N^{1/2}$, where N is the number of satellites tracked. There is no evidence that SA introduces a significant bias. It is possible to reduce the amplitude of the noise at the GPSDO output due to SA by choosing a time constant for the feedback loop that is much larger than the correlation time of the process. The loop is frequently two-pole, and the noise on the output time scale is then effectively the noise on the GPS solution filtered by a single-pole low pass. For a critically damped two-pole loop, the effective noise bandwidth will be about $1/1.6\tau$, where τ is the inverse of the pole frequency. The rms noise at the loop output due to SA, D_{sa} , will then be given by:

$$D_{sa} = (2.1 \times 10^{-12}/(N\tau))^{1/2}. \quad (2)$$

Equation (2) shows that, for sufficiently slow loops, the noise due to SA decreases as $\tau^{-1/2}$. Oscillator noise at Fourier frequencies greater than the pole frequency will add further noise. With quartz crystal oscillators, the choice of time constant is generally limited by environmental noise, for example, resulting from temperature sensitivity, or by non-statistical events such as frequency jumps. Taking a critically damped, two-pole loop with a time constant of 1500 s as an example, we find that, for a receiver tracking an average of 6 satellites, an rms output noise of about 15 ns due to SA is to be expected.

A reduction in the level of SA noise can be obtained by using a longer loop time constant with a superior oscillator such as a rubidium or cesium standard. Alternatively, one might try to obtain higher measurement precision by averaging the output of a quartz crystal GPSDO against a more stable time scale for a long time. In any of these cases it is important to consider at what point the stability will be limited by any noise sources that do not average away rapidly, or that include constant biases, or slowly changing offsets.

Propagation delay due to charged particles in the ionosphere can introduce significant errors in one-way time transfer. The effect can be parameterized in terms of the Total Electron Content (TEC) [10]. This quantity is the number of free electron charges found in a vertical column of area 1 m² integrated through the ionosphere. The group delay G for propagation at the GPS L1 frequency through this column is given by

$$G = 0.54 \text{ TEC} \quad (3)$$

where G is in nanoseconds, and TEC is measured in units of 10¹⁶ per square meter. The delay for tracking a satellite that is not at the zenith is the value given by Equation (3) multiplied by an obliquity factor F that can be expressed in terms of E, the satellite elevation angle in degrees at the observer by the approximate relation [11]:

$$F = 1.0 + 2.74 \times 10^{-6} (96 - E)^3 \quad (4)$$

The spatial and temporal variation of TEC has been extensively studied. The most obvious feature is a cyclic, daily variation. The average amplitude of the daily peak, and its duration, change with the season of the year, the phase of the solar cycle, and the geomagnetic latitude of the observer [10]. There is also considerable day-to-day variability associated with solar activity. In order to estimate the ionosphere effect for one-way time transfer, both the value of TEC and the value of F averaged over the visible satellites must be known. For a receiver with a minimum elevation angle set to 15 degrees at the latitude of the experiments to be described (37.4), this has been found to be about 1.8. Since the local TEC value can reach 75, average peak delays of 70 ns may be expected. The average delay at night falls to a minimum of about 9 ns, so that there is a strong day-night difference in the raw delay.

The GPS system contains a correction that single-frequency receivers can use to compensate for the ionosphere effect in real time [11]. The correction emulates the spatial and time variation with an amplitude that is adjusted depending on observed solar radiation flux. Using this broadcast correction is expected to reduce the ionosphere effect in an L1 receiver by a factor of at least two [10]. When the correction is being applied, the net effect may be either positive or negative, depending on whether the real ionosphere delay is greater than or less than that allowed for in the correction. The remaining day-night difference and the average bias may therefore be of either sign.

The effect of the dry troposphere is accommodated in the receiver by a correction that should be accurate to better than 1 ns in typical conditions.

Equation (1) shows that any error in the antenna position used by the receiver will affect the time estimate. The error is found by averaging, over all satellites tracked, the scalar product of the unit vector to the satellite with the position error vector. The overall effect at any time therefore depends on the symmetry of the visible satellite constellation. At the latitude of the receivers used in these experiments, 37 deg N, we found average sensitivity to vertical position of -2.2 ns per m. The sensitivity to horizontal coordinate errors was at least an order of magnitude smaller, showing that the azimuthal distribution of satellite orbits, as seen by the receiver, was highly symmetrical. This would not be the case if a portion of the sky were obscured. The short-term noise was not significantly increased by a very large vertical position error of 28 m, indicating that the average vertical direction cosine over the satellites tracked was quite constant over time.

Many GPSDOs determine their antenna positions by operating in a navigation mode following turn-on. After a predetermined time, the position data are averaged, and the resulting antenna coordinates are used in the position-hold mode to obtain the GPS time solution with reduced noise. Using typical results for an unobstructed location in US mid-latitudes, one can calculate that averaging for 1 day should generate an rms vertical position accuracy of between 1 and 2 m.

4 NOISE AND ERRORS IN COMMON-VIEW TIME TRANSFER

In common-view time transfer, pseudorange corrections for a predetermined satellite are simultaneously observed at the two locations whose time scales are to be compared. The measurements are averaged over a time of 780 s and then compared, giving the difference between the clock biases. The times of measurements using given satellites are determined by a scheduled published every six months by the BIPM [12]. In the continental US, common-view time transfer is facilitated by the availability, via Internet, of data in the standard GGTTS format [13] from NIST and USNO. The USNO data are referred to UTC(USNO MC), and common-view results are therefore automatically related to this time scale.

The accuracy of common-view time transfer has been extensively studied [12]. With good quality, well-calibrated equipment working over moderate baselines, only a few errors are significant at the level of a few nanoseconds. Since the effects of satellite clock errors, including SA, are completely removed, smaller errors become dominant.

Uncompensated ionospheric delays can cause a daily error of variable amplitude. With small baselines, the ionosphere delay does not appear in the common-view time difference. With baselines exceeding a few hundred km, the ionosphere effects become decorrelated, however, and the effect may be significant.

The single-frequency model in GPS can be used to estimate the typical effect of ionospheric delay on L1, common-view time transfer between two given positions. Using the satellite navigation message data for a chosen day, the ionospheric delay differences for each pass in the BIPM schedule of measurements are calculated using the known satellite positions. The differences are then averaged over 24 hours to give an estimate of the common-view time transfer error for that day if the ionosphere correction were not used in the receiver. If the model exactly predicts the ionosphere, its use in the receiver will reduce these errors to zero. It is known, however [14], that the use of the model actually reduces errors by about a factor of two, and the expected common-view errors should therefore be reduced to about half the value of the error calculated. For the period of these experiments, this analysis for the 4000 km East-West baseline leads us to expect daily average common-view errors due to ionosphere to be about 1-2 ns rms if the receivers correctly apply the single-frequency model. Experiments demonstrating this level of ionospheric effect in multi-channel common view over the baseline USNO-AL have been published elsewhere [14].

Accurate TEC maps obtained by post-processing the data taken by the IGS network are now available, and can be used together with accurate ephemeris data to refine common-view measurements where required. This is especially important over intercontinental baselines, and when the number of observations is limited.

The random noise level in common-view time transfer is one nanosecond or less, and multipath effects are important. These effects are determined by the GPS antenna and its surroundings, and depend specifically on the angles subtended by each satellite. The magnitude of the peak effect on L1-code pseudoranges is typically about 10 ns. Each BIPM schedule consists of a relatively small number of observations of 780-s duration. As the schedule remains almost synchronized with the GPS orbits, the measurements are taken with each satellite at the same angle on successive days, giving rise to an almost constant pattern of multipath delays. The common-view time difference for a given satellite is therefore biased by the very slowly changing difference of the multipath effects at the antennas. Since the measurement times advance by 240 s each day, and the orbits advance by about 237.6 seconds per day, there is a phase change of about 500 seconds in the 6 months for which each schedule is in effect. The resulting rate of change of the average effect depends on the multipath situation at each antenna, which is very difficult to predict. After 6 months, when the schedule is changed, a step change in the multipath effect may be expected.

Satellite ephemeris errors affect common-view measurements to an extent that depends on the distance between the observers. Data derived from observations on the current GPS constellation have recently been

published. The root-sum of squares of the position errors was found to be 4.7 m [15]. With a baseline of 4000 km, the effect of a satellite ephemeris error is reduced by a factor of about 5, resulting in timing errors of about 3 ns. Since the errors are uncorrelated between satellites, the daily average error will be further reduced by the square root of the number of independent measurements made per day. Large, non-statistical errors sometimes occur, and these must be removed by robust signal processing.

5 EXPERIMENTAL DETAILS

The experiments were carried out at two locations: the Standards Lab at the Santa Clara, California site of Agilent Technologies (ATSC); and Agilent Laboratories in Palo Alto, California (AL). These locations are about 17 km apart, and about 4000 km West of USNO in Washington DC. At each location, the time difference between the L1-code multi-satellite one-way GPS time solution and the 1 PPS output of a cesium standard was measured, and hourly averages were logged. The receivers were set to UTC, and the ionosphere and troposphere corrections were enabled. The cesium time scales were also compared with UTC(USNO MC) by common-view measurements using the GGTTTS format, and the US East-Coast BIPM schedule. About 36 common-view measurements were made each day with satellite elevation angles of more than 15 degrees. The one-way time differences were used to steer the cesium standards with time constants of several days. The stability of the cesium standards allowed the one-way and common-view time transfer results to be smoothed over 1 to 2 days, and compared without introducing external noise. The performance of the disciplined cesium time scales was directly monitored using the common-view data. The measurements reported covered a period of 186 days between MJD 51235 and 51420.

At ATSC, a high-performance, programmable, cesium frequency standard was steered by the UTC output of a commercial GPS-disciplined oscillator that used a patch-type antenna. The time difference between the GPSDO 1PPS output and the cesium standard 1PPS was measured each minute with a time-interval counter, and hourly averages were used to control the frequency of the cesium standard using a two-pole feedback loop with a time-constant of 7 days. The servo loop contained a null filter to attenuate one-cycle-per-day noise. The GPSDO used an 8-channel GPS receiver and a high quality quartz oscillator with a loop time-constant of about 1000 s. This system constituted a two-stage GPSDO; the first stage acted as a convenient anti-alias filter, and reduced the data rate necessary in the steering loop. The common-view comparison of the ATSC cesium standard with UTC(USNO MC) was performed according to the GGTTTS format using an independent multi-channel time receiver system that had previously been calibrated at NIST [16]. CV data were downloaded daily from the USNO Web site. The CV antenna was a patch-type, and its coordinates were determined to within 50 cm using L1 differential positioning with respect to an accurately surveyed location.

The measurements at Agilent Laboratories were made using a single 8-channel, modular GPS time receiver and an active ensemble of two high-performance cesium standards. To reduce environmental effects, the temperature of the receiver was regulated. A measured pseudorange correction was available every second for each satellite tracked. The receiver clock was related to the cesium time scale by timing the output pulse each second with a time-interval counter. The resulting single-satellite pseudorange corrections referred to the cesium time scale were low-pass filtered and recorded every 10 seconds. The filters were designed to track the first two time derivatives of the corrections with SA without significant error.

The logged data were used to implement both one-way and common-view time transfer. An hourly estimate of the one-way time difference between the cesium standards and UTC(USNO MC) was obtained by averaging together the 10-second samples for all valid satellites over the preceding 60 minutes. This average was corrected for the GPS-UTC time difference, logged as the one-way time difference, and used to steer the cesium ensemble using a two-pole feedback loop with a time-constant of 8.4 days. The feedback loop contained a null filter for one-cycle-per-day noise.

Common-view data in GGTTTS format was downloaded daily from the USNO Web site, and corresponding 13-minute single-satellite pseudorange averages were assembled from the 10-second samples of the pseudorange corrections. Passes with elevation angles exceeding 15 degrees were accepted as common-view time differences. About 36 points per day were obtained. This non-standard data processing technique was compared with an exact implementation of the GGTTTS format, and was found to be indistinguishable at the level of 0.5 ns. A choke-ring type antenna was used for the AL receiver, and its coordinates were determined using L1 differential positioning with respect to an accurately surveyed location. The antenna coordinates are believed to be accurate to 50 cm. The group delay of the receiver system was calibrated by CV comparison with two independent CV systems that had previously been calibrated at NIST.

6 RESULTS AND DISCUSSION

Figure 1 shows the variation during the period of the experiments of the time difference between each disciplined cesium standard time scale and UTC(USNO MC), as measured by common view. The time differences have been smoothed using a low-pass FIR filter that has a bandwidth of about 2 days, and contains nulls to suppress the daily periodic fluctuations in the common-view measurements resulting from multipath. During the period of the observations, the steering of the ATSC system was interrupted several times by computer failures. During the failures, the longest of which lasted for 4 days, the steering of the cesium standard was frozen at its last programmed value. The AL system also suffered a substantial steering error between MJD 51259 and 51263.

The rms deviations of the ATSC and AL time series shown in Figure 1 are 6.0 and 7.0 ns respectively. The values are not significantly increased by the interruptions in steering. From the known low-frequency spectral density of SA noise assuming that 6 satellites are typically tracked, and the characteristics of the steering loops, we can show that the expected rms noise due to filtered SA is less than 1 ns for each system. Using the loop coefficients and the specified frequency stability of the cesium standards, we calculate expected rms noise contributions of 3.4 and 3.9 ns due to oscillator noise for the ATSC and AL systems respectively. In both systems, the observed rms noise is larger than the sum of the calculated contributions due to SA and cesium standard instability, and, therefore, some other significant noise source or sources must have been present.

To look in greater detail at the accuracy of the one-way time-transfer process that is used to steer the cesium standards, we can examine the difference between the one-way and common-view results directly. The cesium standard time offsets affect the results of both time-transfer methods almost equally, and disappear in the differences. As has been discussed, the CV results should be less affected by most errors. Most of the noise in the differences must therefore reflect noise in the one-way process.

Figure 2 shows the smoothed difference between the common-view and one-way time transfer results for the ATSC and AL systems. If the CV technique results in the transfer of a smaller (earlier) time, the plotted difference is positive. The results for both systems are strikingly similar, showing common, non-random, effects. In particular: (a) both systems show an abrupt step of about -2.5 ns at MJD 51267; (b) both systems show a similar, slow continuous, change of about 10 ns peak-to-peak during 150 days; and (c) there is considerable coherence between the short-term noise shown by the two systems.

A distinct step change in both sets of data occurs at MJD 51267, the date of the adoption of the new CV observation schedule. Because the one-way data do not depend on the CV observation schedule, this jump, demonstrated by both systems, is probably due to the common-view data. Since the ionosphere effect is expected to be smaller than 1 nanosecond in common view, and the schedule change should not affect this to first order, the step is probably due to the effect of multipath. Both the USNO and local antennas contribute to the observed effect, which is the average of common-view time differences within the pass-

band of the smoothing filter. The observed differences presumably show the magnitude of errors due to multipath that must typically exist in common-view measurements using L1-code receivers. The errors would probably increase if the daily average were made over fewer measurements. With longer baselines, fewer satellites will be in common view, and elevation angles will be smaller, leading to larger multipath errors.

The CV minus one-way time differences, $\Delta_{tt, \text{shown}}$ in Figure 2 were each fitted to a cosine function. The function:

$$\Delta_{tt} = \Delta_0 + 7.5 \times 10^{-9} \cos(2\pi(\text{MJD} - 51357)/365.25) \quad (5)$$

was found to be a good fit to both sets of data with Δ_0 , the average offset, as a free parameter. The residuals were unchanged when a quadratic fit was used, but the use of a yearly periodic function seemed physically most reasonable. The rms deviation after fitting was about 2.6 ns in each case. The value of Δ_0 for the fit to the AL data, -2.2 ns, is significant because both time-transfer measurements were made using the same receiver, and the difference is not affected by its delay. The larger Δ_0 value for the ATSC fit, -24 ns, reflects delay calibration and position errors in the GPSDO used.

The difference between the equipment used at each location, and the fact that a thermally controlled receiver was used for both measurements at AL suggest that the slowly changing bias was not an environmental effect. The most probable cause is a failure of the receivers used to compensate correctly for the average ionospheric delay in one-way time transfer, even though they were using the single-frequency model. The average raw ionosphere effect shows an annual variation with a minimum effect in the summer, the point at which the absolute AL difference is smallest. Since both sets of measurements were taken using the same type of receiver, it is not possible to distinguish between inaccuracy in the broadcast single-frequency correction, and a failure of the receivers to apply it correctly. As discussed, the ionosphere effects in one-way time transfer are expected to be much larger than those in common view over the 4000-km baseline used in these experiments.

A cross-correlation function between the data sets shown in Figure 2 between MJD 51270 and 51420 after fitting shows a peak of amplitude 4.5 ns^2 with a correlation time of 1.5 days. The amplitude and correlation time may be affected by the pre-filtering of the data. A linear regression analysis between the two sets of fitted data, omitting periods when the results were known to be unreliable due to missed measurements, confirms that the differences at ATSC and AL are highly correlated, with slope 1.1 and linear correlation coefficient of 0.92.

The correlated short-term noise is probably due to short-term variations in the ionosphere delay, which affects the one-way time transfer to both stations equally. This is not unexpected, since the broadcast model cannot respond to short-term variations in the solar flux. After smoothing, the observed noise is a process with an rms amplitude of about 2.5 ns and a correlation time of about 1.5 days.

During 16 days at about MJD 51290, the GPS Operational Control Segment (OCS) adjusted many of the broadcast values of the satellite interfrequency group delays, T_{gd} , resulting in a change of about 5 ns when averaged over all spacecraft [17]. For correctly operating single-frequency L1 receivers, these adjustments were equivalent to small changes in the average satellite clock biases, and they would not have affected common-view time transfer. The adjustments should have affected one-way time transfer by about 5 ns, but the time-transfer difference data, shown in Figure 2, shows no obvious change of this magnitude near MJD 51290. Short-term noise and the nearby discontinuity at MJD 51267 may be obscuring the effect.

7 SUMMARY

These measurements show that autonomous one-way time transfer is capable of high accuracy. At times of 1 to 2 days, the time-transfer noise seems to be dominated by uncompensated ionosphere effects. The two disciplined cesium standards showed rms deviations of less than 10 ns, with some noise that remains to be completely explained. The steering loop time constants used appear not to have been optimal, and even lower noise levels might be obtainable in the future. The accuracy of the disciplined cesium standard time scales seems to have been significantly affected by a slowly changing bias of about 15 ns peak-to-peak that is possibly associated with the ionosphere or the application of the ionosphere correction in the receivers. This effect would limit the traceability of a GPSDO that was calibrated at a single time and place, and then used elsewhere.

If the time difference found between common-view and one-way time transfer is removed from the data shown in Figure 1 by subtracting the fit given by Equation (5), the remaining noise levels are much closer to those expected. If the origin of the difference can be confirmed, and a way can be found to correct it, more accurate GPSDOs can be made. The accuracy of one-way time transfer should not depend strongly on the location of the receiver, but does depend on good satellite visibility.

The measurements suggest that small step changes in the calibration of common-view time transfer can occur when the observation schedule is changed. Analysis also suggests that multipath effects may cause very slowly changing offsets of several nanoseconds in common-view time transfer. These effects would not depend on baseline, but would presumably be reduced by averaging over many different satellite passes.

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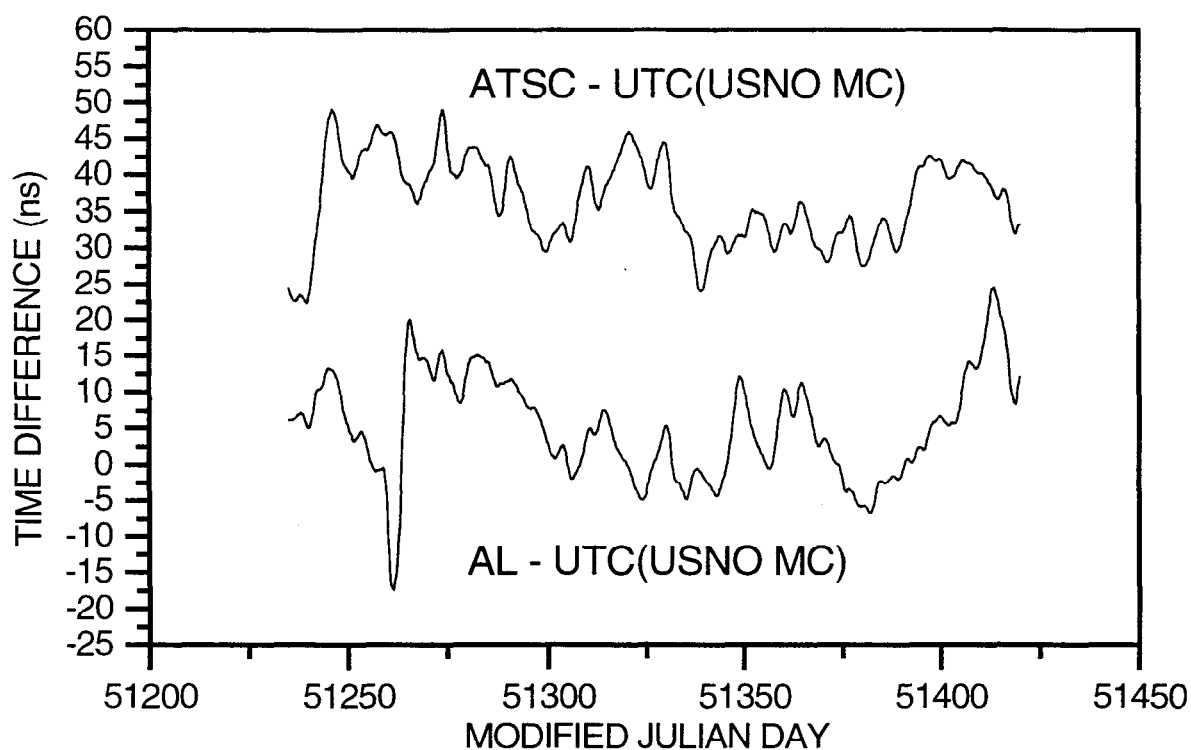


Figure 1 . Smoothed time differences between 1 PPS outputs of disciplined cesium standards at Agilent Technologies, Santa Clara, California (ATSC) and at Agilent Laboratories, Palo Alto, California (AL), and UTC(USNO MC). The rms deviations are 6.0 and 7.0 ns, respectively. Common-view time transfer was used for the measurements, using passes from the US, East Coast BIPM schedule with satellite elevations greater than 15 degrees. The FIR filter used to smooth the raw data consisted of a triangular weighting function with a peak-to-peak width of 4.0 days. The average offset of the ATSC data is due to calibration errors in the GPSDO system. The system at AL suffered a substantial steering error between MJD 51259 and MJD 51263.

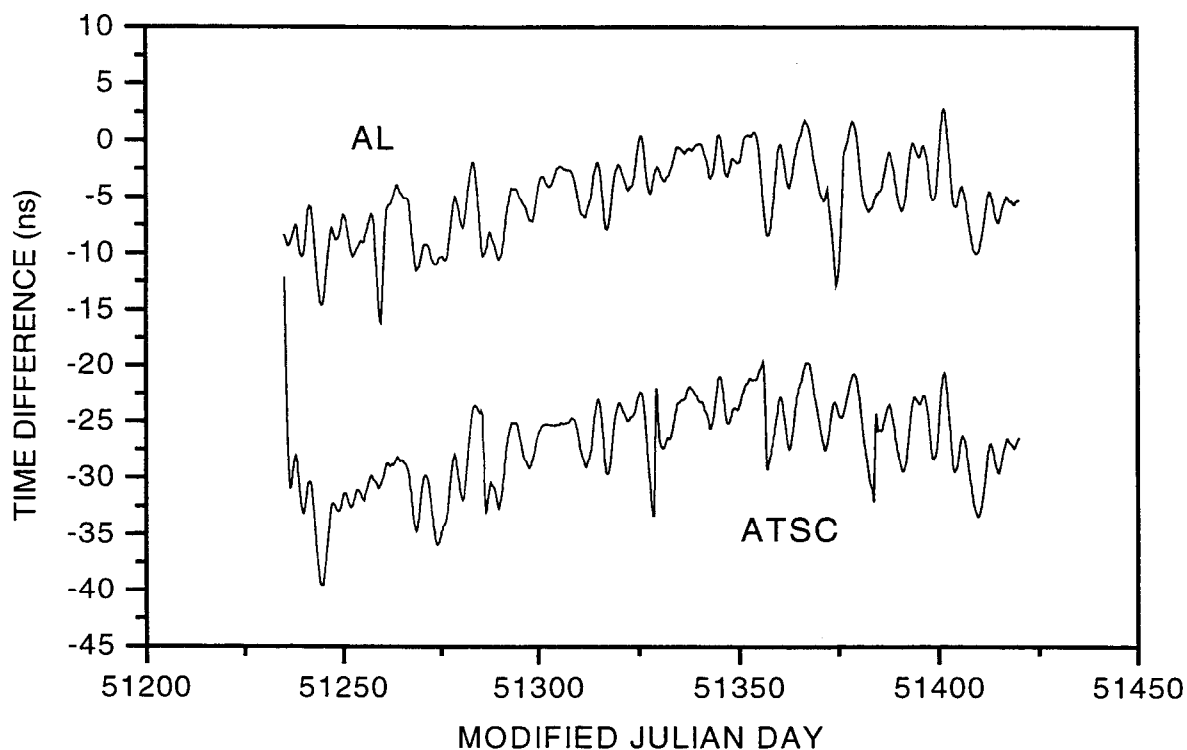


Figure 2 . Smoothed differences between the common-view and one-way GPS time-transfer results for the disciplined cesium standards at Agilent Laboratories, Palo Alto (AL), and Agilent Technologies, Santa Clara, (ATSC) in California. The common-view time transfer was conducted with respect to UTC(USNO MC) at the US Naval observatory, Washington, DC., using passes from the US, East Coast BIPM schedule with elevation angles exceeding 15 degrees. The average value of the ATSC results from calibration and position errors in the GPSDO used. A common receiver was used for both measurements at AL, and the absolute value of the data is therefore significant. Further details and interpretation are given in the text.